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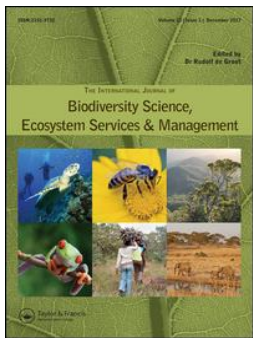
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Ecosystem service supply by European landscapes under alternative land-use and environmental policies

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ABSTRACT

The European Union (EU) 2020 Biodiversity strategy aims at guaranteeing and enhancing the future supply of ecosystem services ('ES') in the member states. In an *ex-ante* assessment of plausible environmental policies, we projected the supply of 10 ES under 3 policy alternatives of land-use change ('Nature Protection', 'Payment for carbon sequestration' and 'Payment for recreational services') in the 27 EU member states (EU27). We assessed changes in supply of individual services across administrative units (at the NUTS-2 and EU27 levels) as well as bundles (at the EU27 level) between 2010 and 2040. Results show that the policy options only marginally affected ES bundles but several services could change substantially at the EU27 level (e.g. energy content from agricultural production and pollination). Wood supply, carbon sequestration and moderation of wind disturbance responded very differently across policy alternatives. At the NUTS-2 level, biocontrol of pests, carbon sequestration, moderation of wind disturbance and wood supply showed the most contrasted deviation from their regional supply in 2010. Finally, while payments for carbon sequestration benefited carbon sequestration as expected, specific payments for recreation services failed to promote them. Our analyses suggest that protecting nature appeared to be the best way of fostering ES supply within Europe.

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1. Introduction

The onset of global change (e.g. climate change, land-use [LU] change, overexploitation of natural resources, pollution) has raised societal awareness that the sustainability of human well being strongly relies on current and future ecosystem functions and properties. The concept of ecosystem services (hereafter 'ES') has provided a conceptual framework (Daily 1997; Díaz et al. 2006; Fisher et al. 2009; Reyers et al. 2012; Guerry et al. 2015) to evaluate mankind's reliance on ecosystems. Most ES have been severely degraded due to human activities (e.g. MEA 2005). Competition for space between activities such as agriculture and nature protection, particularly acute in Europe, is one of the strongest features of the human footprint, along with the increasing demand for natural goods (e.g. food, fuel, materials) that has been driving LU intensification and changes in landscapes (Plutzer et al. 2016). Mediating demand for competing LU is thus the critical challenge for landscape management (Hein et al. 2006) and, hence, for policy.

An increasing understanding of the ES concept resulting from a decade of prolific research on complex socio-ecological systems (Fisher et al. 2009; Abson et al. 2014; Chaudhary et al. 2015), along with past and ongoing national and international assessments (e.g. MEA 2005; Bateman et al. 2013; Díaz et al. 2015), have stimulated the debate about how ES could be incentivised. Several studies have suggested to link the supply of multiple ES to biodiversity conservation (e.g. Cimon-Morin et al. 2013; Zhang et al. 2015; Cordingley et al. 2016; Seppelt et al. 2016), in line with the European Union (EU) Biodiversity Strategy, which makes explicit reference to ES by advocating for the restoration of at least 15% of degraded ecosystems to sustain the supply of services (European Commission 2011). The European Commission has taken up this challenge by integrating the spatial quantification of ES in its Biodiversity Strategy to 2020 (see Action 5 in Target 2). To assist member states in this endeavour, the Mapping and Assessment on Ecosystems and their Services working group was set up to develop a robust analytical

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framework for ES evaluation, fostering a growing number of EU-scale assessments on ES and ES bundles (e.g. Maes et al. 2012, 2015; Mouchet et al. 2017). Economic instruments have also been suggested, such as the market-based 'Payments for Ecosystem Services' (PES) schemes (see Gomez-Baggethun et al. 2010; Banerjee et al. 2013; Naeem et al. 2015). Evaluations of short-to-medium-term impacts indicate that PES may have mixed effects on ES provisioning (e.g. Kinzig et al. 2011; Ulber et al. 2011; Wunder 2013; Strassburg et al. 2014). However, the development of economic and policy instruments related to ES is too recent to draw conclusions on their long-term efficiency.

The prospective use of scenarios enables exploring various policy, socio-economic or climate pathways and their long-term impacts on ES provision (Verkerk et al. 2014; Harrison et al. 2015a). In particular, the Special Report on Emissions Scenarios (Nakićenović et al. 2000) and the more recent Representative Concentration Pathways (Moss et al. 2010) offer a robust framework to support LU scenarios and the opportunity to test their impacts on ES (Schröter et al. 2005; Rounsevell et al. 2006). Other modelling frameworks, like the recent CLIMSAVE initiative (Harrison et al. 2015b), have been applied to explore the outcomes of various scenarios and climate adaptation alternatives on ES supply across Europe (Dunford et al. 2015; Jäger et al. 2015). In addition, recent understanding of ES dynamics has emphasised the need for policy and land management decisions to consider ES as bundles of synergistic and antagonistic services (i.e. associations of ES, repeatable in space or time – Raudsepp-Hearne et al. 2010; Nagendra et al. 2013). Given the interrelations between ES in such bundles, sustainability of ES provision might only be achieved by managing for multiple services (Bennett et al. 2009; Verkerk et al. 2014; Crouzat et al. 2015) instead of targeting one or two specific ES.

Initiating the transition towards the sustainable management of land resources, with the aim to sustain ES supply and human well being in general, depends on understanding the consequences of LU change on ecosystems (Rounsevell et al. 2012). Policies are expected to affect ES supply mainly by direct impacts on LU change (e.g. increased nature protection) or more indirectly by providing those conditions that may lead to LU change (e.g. land abandonment). In this study, we investigated the potential for ES-oriented policy by projecting the supply of 10 ES across Europe following 3 LU policy alternatives: 'Nature Protection', 'PES for carbon sequestration' and 'PES for recreational services'. We asked whether (1) policy alternatives reach their objective (e.g. improving carbon sequestration under the 'PES for carbon sequestration' policy alternative), (2) ES bundles are sensitive to

the differences between policy alternatives and (3) PES alternatives have positive rebounds on non-targeted services.

2. Methods

2.1. Exploring alternatives of environmental policy

To explore the impact of diverging alternatives of environmental policy on ES supply, we used simulation outputs derived from seven global and regional LU models for 27 European countries (i.e. the EU excluding Croatia) (Appendix 1; Lotze-Campen et al. 2013, 2017; Verburg et al. 2013; Stürck et al. 2015a; Verkerk et al. 2016a). This modelling framework included global economic models as well as three models focusing on LU and land cover in Europe. The Common Agricultural Policy Regionalised Impact model (CAPRI; Britz and Witzke 2014) is an econometric model of the agricultural sector used to simulate agricultural policy alternatives in Europe. The European Forest Information SCENario model (Verkerk et al. 2016b) provides detailed information on European forest resource development (incl. species, age, growing stock). The Dynamic Conversion of Land-Use and its Effects model (Dyna-CLUE, Verburg and Overmars 2009) projects LU changes from different sectors on a high-resolution spatial grid based on location factors, LU history, spatial policies and competition between LUs.

Lotze-Campen et al. (2013) and Verburg et al. (2013) applied this modelling framework to explore how LU would change according to four alternative global development scenarios (A1, A2, B1 and B2), as well as to assess how policy options would alter LU in Europe. We relied on their results for three of these policy scenarios, which explicitly considered ES and environmental management. The three policy scenarios were 'Nature Protection', 'Payment for C [carbon] sequestration' and 'Payment for recreational ES [services]'. The 'Nature Protection' variant included measures based on the policy goal to achieve expansion of protected zones, a robust ecological corridor network and strengthened constraints on land-cover changes. Extended areas of nature were modelled to counteract fragmentation and urban sprawl. In the 'PES for C sequestration' scenario, payments were implemented to stimulate carbon sequestration using incentives to protect areas with high soil organic carbon contents, increase carbon storage in forest biomass and promote land conversion towards natural lands. The 'PES for recreational ES' assumed streamlined policies promoting recreational services through incentives and direct payment to farmers or landowners in ES-rich areas, e.g. cultural heritage landscapes

and landscapes with high recreational values. Each of these policy scenarios was elaborated from the A2 global development scenario, which assumes a moderate economic growth and a high population growth resulting in a growing demand of food and feed. For details on all policy scenarios, we refer to Appendix 2, Verburg et al. (2013) and, in the case of 'Nature Protection', to Lotze-Campen et al. (2017).

2.2. Modelling ES supply

We used outputs of the above-mentioned modelling framework to quantify and map the current (i.e. 2010) supply of 10 ES provided by the European ecosystems for EU27 for which data were available. These ES indicators were recreation potential, energy content from agricultural production (shortened 'agricultural production'), supply of wood material (shortened 'wood supply'), fire-risk moderation, flood regulation, regulation of wind disturbance in forests (hereafter 'moderation of wind disturbance'), carbon sequestration, biocontrol of pests, relative pollination potential (hereafter 'pollination potential') and deadwood (described in Table 1, see also Mouchet et al. 2013, 2017).

The agricultural production indicator was based on results of the CAPRI model (e.g. energy content of agricultural yields and other biomass outputs like straw or wood). The EFISCEN model provided estimates (e.g. felling, wood removal, growing stocks) for wood supply, deadwood, carbon sequestration and wind disturbance risk. Dyna-CLUE provided maps to assess the LULC-related parameters used in biocontrol of pests (e.g. habitat suitability and defining the spatial distribution of agricultural lands), pollination potential (e.g. spatial distribution of habitats providing resources for wild bee populations) and recreational potential (e.g. attributing a degree of naturalness to each LULC) models. We used the outputs simulated under the 3 policy alternatives using the same modelling chain (Lotze-Campen et al. 2013) to project the values of the 10 selected ES for 2040.

Dyna-CLUE provided LULC maps that contributed to the downscaling of ES maps at the 1-km² resolution, at the two time steps and for all scenarios. The CAPRI and EFISCEN models provided their estimates at the administrative level and we had to downscale the results of these two models. For CAPRI, we applied the approach described by Pérez-Soba et al. (2015). We disaggregated EFISCEN outputs using information on tree species composition (Brus et al. 2012), harvest likelihood (Verkerk et al. 2015) and the forested area as projected by Dyna-CLUE. Each ES was quantified and georeferenced to the standard INSPIRE reference grid for Europe at 1 km² (available at <http://www.eea.europa.eu/data-and-maps/data/eea-reference-grids-1>) based on the ETRS89 Lambert Azimuthal Equal Area projection.

2.3. Estimating changes in ES and bundles from 2010 to 2040

We first calculated the relative difference between the (non-standardised) projected ES values in 2040 and the (non-standardised) modelled ES values in 2010, at 1 km² resolution. To estimate the deviation in ES supply from the initial state, we expressed these averaged differences of ES values at the continental (EU27) and regional (level 2 of the Nomenclature of the Territorial Units for Statistics or NUTS-2) levels as a percentage of the 2010 supply. Based on previous studies presenting current relationships between ES and EU LU (Mouchet et al. 2017) and projected trends in European landscapes (see Verburg et al. 2013; Stürck et al. 2015a), we produced hypotheses about changes in ES supply under each policy alternative (Table 2).

Prior to the bundle analysis, all indicators were standardised by subtracting the minimum value observed and then dividing by the difference between the maximum and the minimum values observed (Paracchini et al. 2011) for each policy alternative separately, except for the flood regulation index (the calculation of the index already included a standardisation step). To ease interpretation, both wind disturbance and fire-risk indicators were converted by using the formula $1 - x$ (x being the indicator value), thus indicating the moderation of wind disturbance and fire risk.

To capture sets of ES bundles consistently associated throughout Europe for a given date and policy alternative, we built self-organising maps (hereafter 'SOM') to represent the spatial clustering of cells according to the similarity of their supply of each ES, using the 'kohonen' R package (Wehrens and Buydens 2007). A SOM derives from unsupervised learning artificial neural networks and clusters cells sharing common features (Kohonen 1982, 2001). We parametrised SOM to build 2–20 clusters to explore the sensitivity of our results to the number of clusters using the 2010 baseline ES values. The highest silhouette width value (0.35), which compared the compactness and separation of clusters (Rousseeuw 1987), was obtained for three clusters and corresponded to a good compromise between interpretability and the relevance of clusters. To ease comparisons between current and future bundles, we chose to constrain the SOM algorithm to identify three bundles under each policy alternative. Finally, we compared the spatial distribution and the composition of ES bundles, as estimated for the years 2010 and 2040.

3. Results

3.1. EU27-wide changes in ES supply

The average projected supply of each service for 2040 slightly varied across policy alternatives (Table 3).



Table 1. Overview of ecosystem services assessed.

CICES section	CICES group	Indicator	Code	Description	Unit	References
Cultural	Physical and experimental interactions	Recreation potential index	RPI	Potential provided by ecosystems, depends on the presence of certain ecosystems (i.e. forest, coastline), certain ecosystem characteristics (i.e. naturalness) and their accessibility	Adimensional continuous index	Paracchini et al. (2014)
Provisioning	Biomass (nutrition, materials, energy)	Agricultural production	ECO	Energy content of agricultural production as an estimate of food, feed and fibre production using CAPRI model	MJ/ha	Pérez-Soba et al. (2015)
	Biomass (materials, energy)	Wood supply	WS	The volume of stemwood extracted from forests for material and energy use. The supply of wood is determined by the growth and structure of forests modelled using EFISCEN and the demand for forest products	m ³ /km ² forest/year	Nabuurs et al. (2007), Verkerk et al. (2014)
	Mediation of flows	Fire risk index ^a	Fire	Based on fire occurrences between 2001 and 2010 extracted from the FIRMS MODIS fire/hotspot data set (Davies et al. 2009), vegetation vulnerability to wildfires, climatic conditions and topography	Probability	Mouchet et al. (2012, 2013)
Regulating and maintenance	Mediation of liquid flows	Flood regulation supply indicator	IFS	Related to flood regulation. Based on the variability of the peak discharge at the outlet of a catchment in dependence of LU and soil distribution. Estimated using the hydrological model STREAM representing river catchments, land cover, LU and management	Adimensional continuous index	Stürck et al. (2014)
	Mediation of air flows	Wind disturbance risk in forests ^a	Wind	Based on the exposure (given by forest area and total growing stock) and vulnerability (related to age structure and species composition) of forest, modelled with EFISCEN, to wind disturbance	Adimensional index	Schelhaas et al. (2010)
	Climate regulation	Carbon sequestration	Cseq	Amount of carbon that is sequestered from LU, LU change and forestry through a bookkeeping approach. Carbon budgets are calculated at 1 km ² based on changes in soil and biomass stocks and an emission factor. LU data are provided by Dyna-CLUE and forest-specific data by EFISCEN	C/km ² /year	Schulp et al. (2008), Böttcher et al. (2012)
	Pest control	Species providing natural control of invertebrate and rodent pests	BC	The number of species providing the ES results from the overlaid distributions of species providing pest control. Based on the biodiversity data set published by Maiorano et al. (2013), spatialised using Dyna-CLUE	Number of species	Following Civantos et al. (2012)
	Lifecycle maintenance, habitat and gene pool protection	Relative pollination potential	RPP	Related to the availability of floral resources, bee flight ranges and the availability of nesting sites. The index integrates land cover (Dyna-CLUE), floral and nesting availability in agricultural lands (CAPRI), High Natural Value Farmland data and road network	Adimensional continuous index	Zulian et al. (2013)
		Deadwood	DW	Indicator for biodiversity in forests related to the resource availability (i.e. standing and downed deadwood, stem residues) and species richness modelled with EFISCEN	Mg dry matter/km ² forest	Verkerk et al. (2011)

^aWind disturbance risk and fire risk indices are related to the vulnerability of an ecosystem to wind or fire. Consequently, the higher the value, the higher the vulnerability. To assess the corresponding services (i.e. regulation of wind disturbance and fire risk), we used the formula $1 - x$ (x being the indicator value).

Models are presented in Mouchet et al. (2013, 2017) but the detailed description of the quantification of services is given in the cited references. The validation and uncertainty associated to ES maps are discussed in cited references and in Schulp et al. (2014) for climate regulation, flood regulation, pollination and recreation indices. CAPRI: Common Agricultural Policy Regionalised Impact model (Britz and Witzke 2014); EFISCEN: European Forest Information SCENARIO (Verkerk et al. 2016b); Dyna-CLUE: Dynamic Conversion of Land-Use and its Effects model (Verborg and Overmars 2009).

See Section 2.1 for further details on CAPRI, EFISCEN and Dyna-CLUE.

Table 2. Summary of the hypothesised effects of policy scenarios on ecosystem services in our framework.

	Nature Protection	PES for C sequestration	PES for recreational ES
¹ RPI	Increasing outdoor recreation due to the expansion of protected areas beyond Natura2000 and restrictions on human intervention and land cover changes within them	A slight decrease in outdoor recreation due to increased forest extent and limited grassland conversion	Limited effect due to maintenance of management system delivering some ecosystem service. However, the contribution of agricultural land to outdoor recreation is relatively limited compared to protected areas and natural/semi natural land which are not much affected by this policy alternative
² ECO	Agriculture intensification of the remaining cultivated lands, to compensate the loss of agricultural lands and to sustain the demand for agricultural production	Spatially heterogeneous effect: decreases in grasslands due to restrictions to conversions, increases in other areas due to agriculture expansion/intensification to meet the agricultural production demand on less available agricultural land	Spatially heterogeneous effect: decreases in agricultural areas targeted by the policy, increases in other areas to counter this
³ WS	Spatially heterogeneous but overall reduced wood supply due to restrictions on management in protected areas.	Spatially heterogeneous but overall reduced wood supply due to incentives to store more carbon	Mixed effect
⁴ BC	Overall increase but regionally heterogeneous because of the mixed effects of projected land use policies : biocontrol might decrease with the loss of pests as an answer to the expansion of protected areas but could increase with the intensification in remaining agricultural lands		
⁵ Cseq	Spatially heterogeneous with local increase of carbon sequestration due to increased natural lands, less gross conversions and restrictions on wood removals	Overall increasing carbon sequestration in biomass due incentives to store more carbon in forest biomass	Regionally contrasted as displacement effects may occur. Smaller contrasts expected than for the "Nature Protection" scenario, as the amount of forest doesn't change
⁶ DW	Minor increase in deadwood supply in most regions due to reduced wood harvest either to protect nature or stock carbon.		
⁷ Fire	Almost no change in the overall level of supply due to maintenance of management system delivering some ecosystem service. In some regions, propagation of wildfires may be facilitate by a reduced management intensity, land abandonment and increasing fuel loads (biomass)		
⁸ IFS	Almost no effect on flood regulation	Almost no effect on flood regulation	
⁹ RPP	Mixed effects resulting in an overall decrease: forest expansion increases pollination potential near the edges of forests but decreases it in the cores. Restrictions on LU conversion within the enhanced protected network will mostly prevent decreases rather than determine significant increases		
¹⁰ Wind	The overall trend might an increase in the moderation of wind disturbance, preserving nature for conservation purposes or carbon sequestration or recreational activities will locally decrease its supply. Indeed, it will favour larger share of old trees that are more vulnerable to wind disturbance		

¹RPI – recreational potential;²ECO – agricultural production;³WS – wood supply;⁴BC – biocontrol;⁵Cseq – carbon sequestration;⁶DW – deadwood;⁷Fire – fire risk moderation;⁸IFS – flood regulation;⁹RPP – pollination potential;¹⁰Wind – moderation of wind disturbances.

According to the projections, all policy alternatives would result in a decreasing supply of pollination potential (–5%, –10.5% and –10.7% under 'Nature Protection', 'PES for C sequestration' and 'PES for recreational ES', respectively). In contrast, agricultural production and biocontrol of pests are projected to increase, regardless of the policy alternative. The supply levels of fire risk moderation, deadwood and flood regulation change only marginally and would remain similar to the baseline. Wood supply, carbon sequestration, moderation of wind disturbance and, to a lesser extent, recreational potential are the only ones showing a marked difference between policy alternatives. Wood supply decreased in the 'PES for C sequestration' policy alternative, remained constant in the 'Nature Protection' policy alternative and

increased in the 'PES for recreational ES' policy alternative. For carbon sequestration, only the 'PES for C sequestration' is expected to enhance carbon sequestration (e.g. +9.4%, against –15.2% and –29% under the 'Nature Protection' and 'PES for recreational ES', respectively).

The two PES policy alternatives benefited mainly the forest-related services, agricultural production (+8.9% for 'PES for C sequestration' and +12.6% under 'PES for recreational ES') and biocontrol of pests (+5.5% for 'PES for C sequestration' and +4.9% under 'PES for recreational ES'). This policy alternative led to the overall higher supply for 3 out of 10 ES: recreation potential (+3.1%), agricultural production (+13.4%), biocontrol of pests (+5.7%)

Table 3. Trends in ES supply between 2010 and 2040.

		Average supply in 2010	Nature Protection (%)	PES for C sequestration (%)	PES for recreational ES (%)
Cultural services					
Recreation potential	RPI	0.3	3.1	−0.8	−0.8
Provisioning services					
Agricultural production	ECO	0.98	13.4	8.9	12.6
Wood supply	WS	0.84	−0.7	−13.5	6.8
Regulating and maintenance services					
Biocontrol of pests	BC	0.38	5.7	5.5	4.9
Carbon sequestration	Cseq	0.51	−15.2	9.4	−29
Deadwood	DW	0.08	2.2	2.4	1.9
Moderation of fire risk	Fire	0.51	−0.01	−0.01	−0.01
Flood regulation	IFS	0.26	0.03	−0.1	−0.3
Relative pollination potential	RPP	0.12	−5	−10.5	−10.7
Moderation of wind disturbance	Wind	0.06	8.3	9.3	−0.8

In the first column, the average standardised ES levels of supply in 2010 (dimensionless) are given as a reference to ease the comparison across ES. In the other columns, trends are expressed as a percentage of the 2010 average supply and calculated as the difference of (non-standardised) ES values between of the two time steps divided by the (non-standardised) average 2010 supply.

and, as already mentioned, in the case of pollination potential, a lower decrease than under other alternatives. Likewise, biocontrol of pests may increase in strongly intensified remaining agricultural lands but may decrease in the extended natural (protected or not) areas because this ES is, by definition, related to the presence of agricultural lands. Indeed, the smallest changes (e.g. biocontrol of pests and moderation of wind disturbance) and the higher decreases (e.g. wood supply and carbon sequestration) are only projected under PES alternatives.

3.2. Regional changes in ES supply

Obviously, trends at the scale of the whole EU may obscure regional and local trends. Indeed, an overall projected trend could result from the maintenance of similar levels of ES supply in 2040 as compared to 2010, from the compensation of regional/local gains and losses of supply, or from a combination of both patterns. Overall, regional changes in ES supply tend to

be consistent with EU-wide change (see Appendices 3–5) but biocontrol of pests, carbon sequestration, moderation of wind disturbance and wood supply show the most contrasting regional trends (Figure 1(a,b)). The projected state of biocontrol of pests is overall higher than the initial 2010 state but much contrasted from one NUTS-2 region to another, regardless of the policy alternative. Greater losses are expected in southern Spain and Portugal, NE Balkans, United Kingdom and Ireland, and from Belgium to Denmark. Greater gains are projected in Southern Finland and Sweden, Estonia, Southern France, Tyrol and in the Italian regions from Liguria to Abruzzo. Carbon sequestration is projected to consistently drop except in the ‘PES for C sequestration’ policy alternative (Appendix 4). However, patterns of changes in the supply of carbon sequestration are similar among alternatives.

Conversely, continental trends in ES supply are representative of regional ones in the case of deadwood, with a very few regional exceptions, pollination potential and agricultural production. The average agricultural

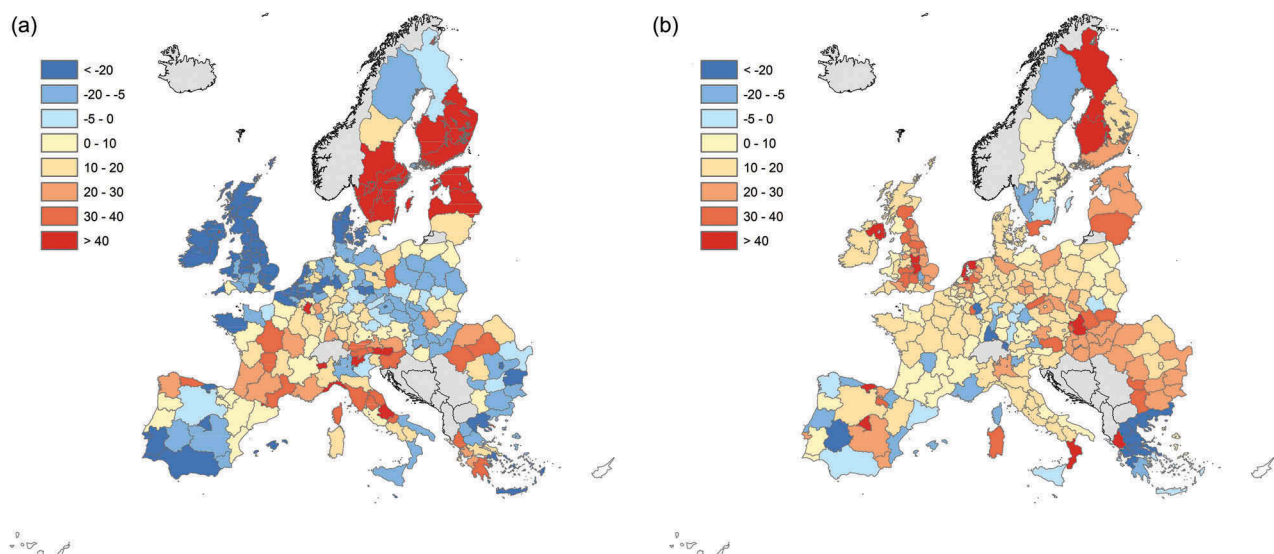


Figure 1. Predicted regional deviation of (a) biocontrol of pests and (b) energy content of agricultural biomass, under the ‘Nature Protection’ scenario, from their 2010 baseline supply. Regional changes are given as the average absolute difference at the NUTS 2 level between 2040 and 2010 ES value.

production is projected to increase by 2040 in already intensive agricultural regions like the central Po Plain in Italy, eastern England, the NE German Plain and Saxony (SE Germany), SW Slovakia and Hungary, in all projected policy alternatives. Decreases are expected to occur consistently across policy alternatives, in a few regions including southern Spain and Catalonia, the SE Germany (Bavaria and Baden-Württemberg) or Bulgaria. This result is in agreement with the already identified trend of a polarisation for agricultural production in Europe (Stürck et al. 2015a), with increases in highly competitive

regions that have to compensate for land abandonment in some marginal areas.

3.3. Changes in ES bundles

Using self-organising maps, we identify three ES bundles supplied by three clusters of sites (i.e. pixels) sharing common characteristics in ES supply (Figure 2). The segregation of pixels into clusters is mainly driven by their potential to supply agricultural

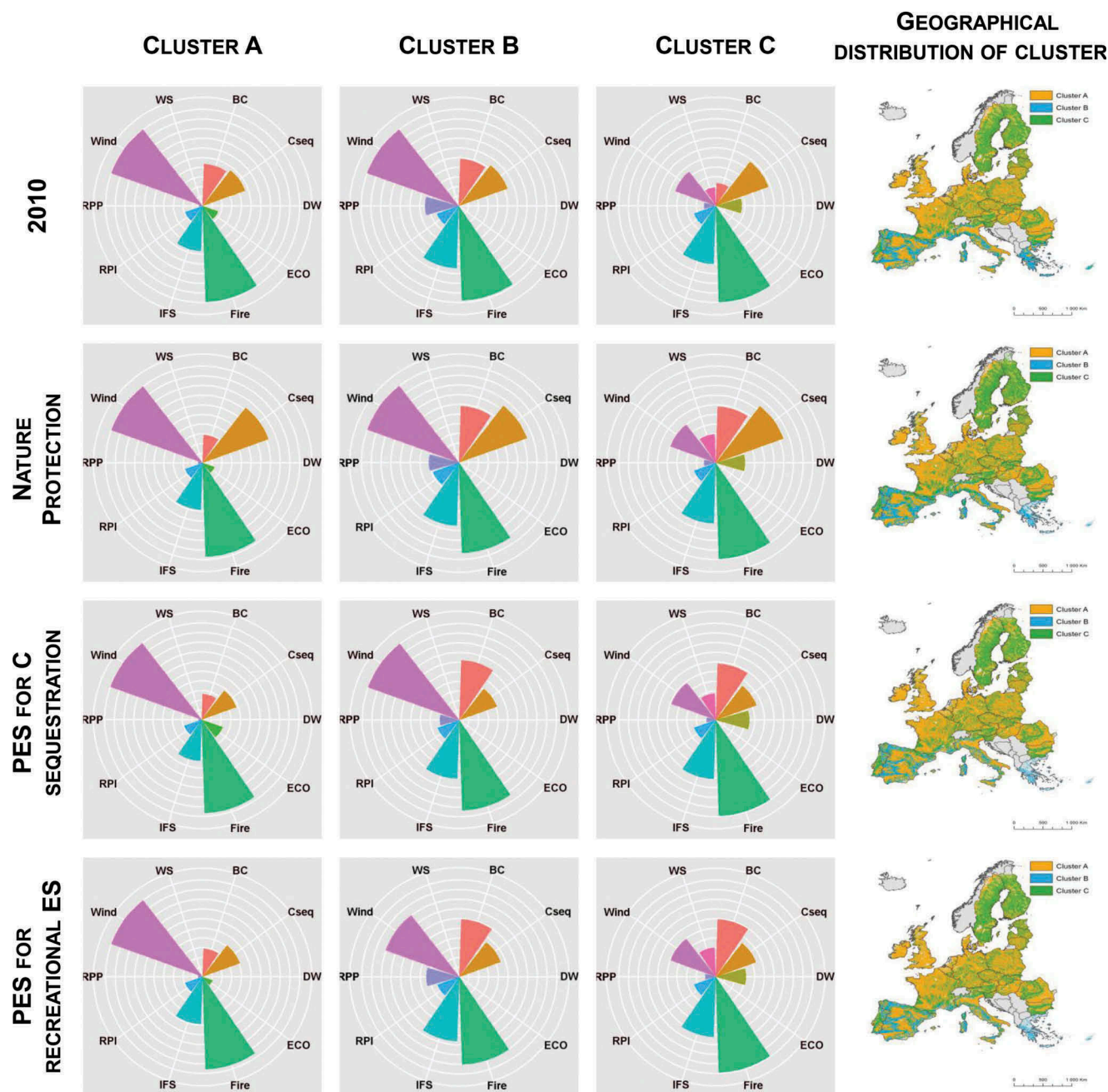


Figure 2. Geographical distribution of current and projected ES bundles. ES bundles are represented on the left panel and the spatial distribution of the bundles on the right. The length of the chunks on the left panel is proportional to the average supply of each ES over the pixels in the cluster. Pixels on the map are coloured according the clusters in the left panel. The names of the ES on A are abbreviated: 'BC': biocontrol of pests; 'Cseq': carbon sequestration; 'DW': deadwood; 'fire': fire risk moderation; 'IFS': flood regulation; 'ECO': agricultural biomass; 'RPI': recreational potential index; 'RPP': relative pollination potential; 'WS': wood supply; 'wind': wind disturbance moderation in forests.

production (cluster A) on one hand, and wood and deadwood (cluster C) on the other hand, regardless of the policy alternative.

Bundles thus reflect LU: cluster A overlapped with pastures and arable lands, cluster B with semi-natural areas (but not forested) and cluster C with forested areas.

The ES bundles show very similar patterns between the 2010 baseline and policy alternatives except for cluster B, under the 'Nature Protection' and 'PES for recreational ES' policy alternatives. Numerous sites from 'pastures and arable lands' (cluster A) and 'semi-natural lands' (cluster B) bundles identified for the 2010 baseline, shifted into cluster C in 2040, due to forest regrowth. Compared to 2010, the area of cluster B decreased substantially, and sites remaining in the 2040 cluster B were those specialised in flood regulation, recreation potential and, to a lesser extent, pollination potential. This is likely linked to the strong increase in pasture and grassland projected under the 'PES for recreational ES' policy alternative particularly in Spain, Italy and Greece. The most significant difference between clusters A and C (current or projected) lies in the level of biocontrol of pests and carbon sequestration, regardless of the policy alternative. The contribution of moderation of wind disturbance to bundles A and B may not represent an actual high supply of the service by the ecosystem but a lack of risk due to the absence of forested areas. Indeed, the moderation values are given by *1-risk values*. In the case of moderation of wind disturbance, where there is no forest cover, there is no risk of disturbance. Consequently, the regulating service is assumed maximal. This is also true for fire risk moderation in pasture and arable lands. Indeed, we estimated fire risk using observed occurrence of fires in Europe. The actual wildfire occurrences in managed ecosystems are likely to be quickly detected and controlled thanks to a heightened surveillance. For technical issues (i.e. the self-organising maps algorithm used did not accept missing values), we chose to replace the missing values of ES supply by 0 instead of removing all sites with at least one missing value for one ES, thereby substantially reducing our data set. This contributes to an underestimation of the level of flood regulation in Greece where it was not quantified.

4. Discussion

Our analyses reveal that future policy options have leverage to change current landscape multifunctionality on the medium term. This phenomenon is illustrated by the 'forest' cluster, within which not only wood supply but also other services were projected to be affected by policy options. The average change in

the supply in a given ES between 2040 and 2010 is rather similar between policy alternatives, except for wood supply, moderation of wind disturbance, carbon sequestration and, to a lesser degree, recreational potential. In the following sections, we discuss our results for each of our research questions.

4.1. To what extent do environmental policies reach their objective?

The projected changes in ES supply did not always match with the expected trends in ES supply (as described in Table 2). Our results suggested that the PES for carbon sequestration successfully promoted carbon sequestration, but that PES for recreational ES did not foster the targeted service. The projected increase in carbon sequestration under the 'PES C sequestration' results from incentives to limit the harvest of wood leading to a stronger accumulation of carbon in biomass and soil. It is worth noting that results depend, to a large extent, on the time frame considered in this study. In the longer term, the measured increment considered in this policy alternative may lead to saturation of the forest biomass carbon sink, as the growth rate of mature forests will eventually decline.

The recreational potential index is based on the assumption that areas with a higher degree of naturalness (i.e. forests, semi-natural grasslands) have a higher potential for outdoor recreation linked to the enjoyment of nature. Thus, the indicator appeared to be highly sensitive to the expansion of protected areas beyond the Natura2000 network and strengthened constraints on land conversions (e.g. expansion of natural areas, including forest, semi-natural vegetation as well as abandoned pasture and arable land) given by the storyline of 'Nature Protection'. It was less sensitive to local transitions of crops or arable lands to (intensively) managed grasslands or pastures induced by both PES policy alternatives, since these classes have a similar degree of naturalness. Indeed, 'PES for recreational ES' entails very few changes in areas attractive for recreational activities and in the determinant landscape parameters between 2010 and 2040, e.g. attractive ecosystems like sea coasts and inland water are assumed to remain static. The projected changes in our recreational potential indicator value are primarily driven by LU transitions in these attractive ecosystems rather than an expansion or loss of the total area suitable to recreational activities. It is important to note that the 'PES for recreational ES' assumes that recreational services are promoted in already ES-rich lands. Only the 'Nature Protection' policy alternative entails enough expansion of the lands with a higher degree of naturalness (i.e. protected areas network) and constrains on land-cover

change that lead to a minor, but not negligible, increase of the service.

In the PES policy alternatives, however, the protected areas network remains unchanged and PES schemes would not counteract the loss of semi-natural areas, the expansion of built-up areas and forest, and the intensification of remaining agricultural lands. In our study, protecting nature (without targeting a specific service) proves to be the most beneficial for all ES. In accordance with Haines-Young et al. (2012), the estimated changes in ES supply would be spatially heterogeneous; forested, semi-natural and mosaic landscapes would enhance ES supply, but stronger restrictions on land-cover conversion in protected sites could entail a more intensive use of unprotected areas as well as less abandonment of agricultural land.

The mixed efficiency of the policy alternatives to foster ES supply might also result from some overarching trends acting at EU level under A2 marker policy alternative (e.g. urban expansion, forest consolidation, intensification of agricultural lands) that policies like 'Nature Protection' can attenuate but cannot entirely offset. ES supply may also respond to other pressures than LU transitions. The distributions of vertebrate species underpinning the biocontrol of pests model mainly rely on species distribution modelling and might thus be more sensitive to climate changes than to LU transitions (Barbet-Massin et al. 2012; Conlisk et al. 2013; Sohl 2014).

4.2. Will ES bundles be sensitive to policy alternatives?

The composition of projected bundles was found to be quite close to the current bundles, as changes in several ES supply were marginal at the EU27 scale. In fact, changes essentially related to the spatial distribution of bundles and were driven by LU trajectories, regardless of the policy alternative and despite projected changes in the supply of some ES. In particular, the ongoing forest cover expansion and land abandonment over Europe (Fuchs et al. 2012) might eventually conflict with the production of food, feed and fibre. In that case, the remaining agricultural lands should supply a growing amount of agricultural production per unit area. This should be particularly true under the 'Nature Protection' policy alternative that implied a smaller surface of remaining agricultural lands, than the PES policy alternatives, potentially leading to a stronger intensification (per hectare) to meet the increasing demand for agricultural products. Consequently, the relative (per hectare) food production is the highest under the 'Nature Protection' policy alternative, but the absolute food production is slightly lower in this alternative compared to both the PES alternatives.

Our analyses focused on ES provided by European landscapes. However, impacts of LU strategies and policies depend on the system boundaries that are considered (Verkerk et al. 2014). For example, protecting nature might not only result in societal benefits within Europe but may also displace the negative LU impacts outside Europe (Mayer et al. 2005; Lotze-Campen et al. 2017) and/or induce the replacement of raw materials (e.g. wood) by more polluting materials (e.g. fossil fuels, concrete, steel). As a consequence, the areas projected to supply higher levels of ES might balance out those supplying less when scaling up ES supply at the global level, as long as areas of supply and demand remain spatially and temporally connected. We could not compare the evolution of the demand to that of projected changes in supply in our work but other studies suggest mismatches between an increasing demand for ES and their future supply (Stürck et al. 2015b) or potential trade-offs between provisioning and non-marketed services (Verkerk et al. 2014). Further efforts are required to fully comprehend the future of ES bundles in response to evolving demands.

4.3. Will PES variants have positive rebounds on non-targeted services?

PES schemes are very likely to affect non-targeted services. For example, fostering recreation services to meet an increasing demand could happen at the expense of habitat and agricultural services (Haines-Young et al. 2012). In our case, PES policy alternatives generated similar trends in ES supply (i.e. if one non-targeted ES tends to increase at the EU level in one policy alternative, it should also increase in the other PES policy alternatives), with the exceptions of carbon sequestration, moderation of wind disturbance and wood supply. Wood supply decreased in the 'PES for C sequestration' policy alternative remained constant in the 'Nature Protection' policy alternative and increased in the 'PES for recreational ES' policy alternative. As mentioned in the previous section, incentives from the PES for C sequestration scheme reduced the amount of wood supplied in favour of increased carbon sequestration in forest biomass. In contrast, the 'Nature Protection' policy alternative appears as the most effective to foster ES as compared to the two PES policy alternatives, predicting higher supply and weaker decreases for many services. Indeed, protecting nature most likely protects the complex mechanisms linking biodiversity, habitats and ES. Besides, biodiversity is entwined with more ES than a given service could be with all others. This result supports claims to rethink the long-term sustainability and efficiency of PES schemes (Farley et al. 2010). Protected areas (Palomo et al. 2014; Castro et al. 2015), as well as biodiversity (Díaz et al. 2009; Harrison et al. 2014),

have been proven to be significant ES providers. Consequently, PES schemes not straightforwardly targeting natural areas and biodiversity may be less efficient at promoting multiple ES than expected. Assuming that protecting carbon stock areas might also protect biodiversity is misleading as carbon hotspots are not always spatially congruent with biodiversity hotspots (Strassburg et al. 2010; Locatelli et al. 2014). The effectiveness of a policy promoting carbon sequestration strongly depends on the time scale considered. Storing carbon in forests can be only a temporary solution, as the storage capacity will eventually saturate, or be lost due to disturbances (Nabuurs et al. 2013). Thomas et al. (2013) also estimated that combining carbon and biodiversity conservation strategies would greatly outperform both carbon-only and biodiversity-only conservation strategies because of the spatial mismatch between carbon stocks and biodiversity. This calls for spatially diversified policies and management strategies, which consider all LU functions (cf. Nabuurs et al. 2013). Not surprisingly, current PES schemes and climate change mitigation tools implemented alone appear not to sufficiently reduce biodiversity loss (Hein et al. 2013) and could have greater co-benefits for human society and biodiversity if priority areas were selected so as to maximise multiple ES (Locatelli et al. 2014), in Europe as in (developing) tropical regions.

5. Conclusion

LU transitions will occur under our three environmental policy alternatives but it is very challenging to foresee and model how these transitions will induce changes in ES supply and bundles. Lawler et al. (2014) highlighted the difficulty to anticipate rebounds of US environmental policies and correctly identifying the drivers of change (i.e. political, market-based and/or biophysical). The authors acknowledged the complexity to anticipate most drivers of LU changes in the coming future, i.e. climate change, market, new technologies, societal and political changes. In that sense, the policy alternatives built are only a reflection of policies. Likewise, these findings also depend on our choice of ES and indicators. Consequently, our attempt to predict future ES supply should be taken with caution as a small set of possibilities at a very coarse scale is explored, but it lays the foundations for further predictive studies on LU and ES, across EU. In addition, future changes in ES targeted by PES schemes might be very different from expectations if LU transitions are not heavily constrained towards the most appropriate LU to meet goals of these PES schemes (i.e. more natural and less managed LU in most cases).

Two important conclusions emerging from our results are that

- (1) services are related to each other and to LU in such intricate ways that designing environmental

policies targeting very specific ES will most likely fail to ensure multi-ES supply or even fail to significantly enhance the supply of the targeted ES;

- (2) converting a managed LU to a 'less managed' or 'more natural' LU may not be sufficient to improve ES supply. Further efforts are required to define which specific LU transitions would be the most beneficial to ES and bundles.

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